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Wind Tunnel Tests of a 42 Inch Diameter Self-Starting Autogyro Rotor

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The autogyro is being investigated for potential use as a small unmanned air vehicle for Navy electronic warfare missions. This paper presents wind tunnel test results for a 42 inch diameter unpowered rotor with coupling between feathering and flapping that allows for self-starting from a vertical descent. Aerodynamic performance is given for several blade pitch angles and angles of attack.

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WIND TUNNEL TESTS OF A 42 INCH DIAMETER SELF-STARTING AUTOGYRO ROTOR

Steven K. Tayman, Code 5712

INTRODUCTION:

Autogyros show great potential as small unmanned air vehicles for Navy electronic warfare missions. The rotor provides high lift at low speeds and the vehicle is very compact when folded. In an effort to simplify the vehicle, the feasibility of using tail surfaces for stability and control rather than the conventional rotor cyclic and collective pitch controls was explored. Without collective pitch control, the rotor would only self-start at zero to negative pitch angles which are inefficient for forward flight.[1] This rotor model wind tunnel test addressed the self-starting issue and the performance of an autogyro rotor operating at low blade chord Reynolds numbers.

Wind tunnel test results are presented for a small two-bladed autogyro rotor with high coupling between flapping and feathering such that when the rotors flap upward they feather to a negative pitch angle. This type of hinge is commonly termed a Delta-3 hinge. The purpose of the offset Delta-3 hinge in this application, is to allow the rotor blades to fold along a fuselage and be self-starting from a vertical free fall with a rotor angle of attack of 90 degrees. The average blade chord Reynolds number varied from 150,000 to 219,000. The effect of varying Reynolds number on aerodynamic performance is presented. The performance for different blade pitch angles are compared. In addition to self-starting from a vertical free fall, the Delta-3 hinge allowed self-starting at angles of attack above 10 degrees with blade pitch angles of up to 4 degrees measured at a flap angle of zero.

BACKGROUND:

The U.S. Navy is interested in the application of small unmanned autogyros as expendable decoy vehicles launched from a

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ship and capable of flying at ship-like speeds. An autogyro is particularly suited to this mission because of its compactness, simplicity, and slow speed capability. The current autogyro decoy design concept requires that the vehicle be deployed from a mortar tube type launcher by a solid rocket motor. In storage, the rotor hub is at the rear of the fuselage and the blades are folded forward along the fuselage. The deployment scheme is illustrated in Fig. 1. At apogee, the rotor blades are released and blown back from alongside the vehicle's fuselage and assume a large coneing angle of about 20-30 degrees. The rotor blades due to the Delta-3 hinge will assume a negative pitch angle. The negative pitch angle will cause the rotor to begin autorotation in the desired direction of rotation. As the rotor coneing angle decreases with increasing rotational speed and the resulting centrifugal force, the pitch angle increases to a small positive angle (0 to 4 degrees). A positive blade pitch angle is required to achieve the best performance possible in forward flight.[1] Transition to forward flight from the autorotative descent is accomplished by rotating the body about 90 degrees relative to the mast, unfolding the tail surfaces, and applying power to the tractor propeller.

EXPERIMENTAL APPARATUS:

The experiment was conducted in NRL's low speed wind tunnel facility, the Off Board Testing Platform (OBTP). The closed loop tunnel has a four foot square test section and is capable of speeds from 15 to 200 knots. The settling chamber has a honeycomb flow straightening section followed by 4 screens. The contraction ratio is 6.8 to 1.

The test section has a sting type model support capable of -12 to 30 degrees angle of attack and +/- 30 degrees of yaw. An internal strain gage balance measures all six forces and moments. Output from the balance goes through signal conditioners and is read by a PC based data acquisition system. Other data gathered by computer includes the stilling chamber pressure, test section static pressure, total temperature, pitch position, and yaw

position.

AUTOGYRO MODEL AND INSTRUMENTATION:

The autogyro model has a 42 inch diameter two-bladed rotor with a 1.75 inch chord (see Fig. 2). The diameter is as large as wall interference considerations would allow in the 48 inch by 48 inch test section. The rotor blades were made from wooden model helicopter blades with a 15% thick flat-bottomed airfoil, no taper, and no twist. The hub has a flapping offset of 1.25 inches and permitted a maximum coneing angle of approximately 21 degrees. The blade pitch link arms were fixed and mounted off the axis of the flapping pin, so as to couple blade feathering with blade flapping. Two different amounts of coupling were tested by fabricating different length brackets to which the pitch link arms were attached. The pitch link arm lengths were adjusted to set the blade pitch angle.

A plywood body with a 2.625 inch square cross section served as an aerodynamic fairing for the balance. The mast is a 0.375 inch diameter steel rod which positions the rotor 4.125 inches above the center line of the body. The mast was mounted perpendicular to the body to allow adequate clearance between the blades and the sting. The rotor was mounted sideways in the tunnel to allow the rotor to be spun up by hand to help start autorotation when necessary. Rotor rpm was measured using a hall effect sensor and two magnets mounted on the hub. A small three wire cable powered the sensor and provided the output signal. The accuracy of the measured rpm was about +/- 10.

TEST RESULTS AND DISCUSSION:

Initially, the coupling of feathering with flapping ($d\theta/d\beta$) was set at -0.6, that is for every degree of upward flapping there was -0.6 degrees of feathering or pitch change. To test whether this magnitude of coupling was sufficient, the rotor was tested at a 90 degree angle of attack to simulate vertical descent. With the blade

pitch set at 3 degrees (rotor blade pitch angles were measured with a flap angle of zero), it was discovered that while the rotor would self-start in the right direction, it would not go to the high rpm expected. For example, at a tunnel speed of 24 fps, the rpm was only 199, when it was expected to be over 1000. Analysis of the data indicated that most of the rotor blade was in a deep stall condition with an average angle of attack of about 40 degrees. It was observed over the course of testing that there were often two stable rpms for a given rotor pitch angle, alpha, and airspeed. A low rpm state where much of the rotor blade is stalled (stall autorotation) and a higher rpm state corresponding to full autorotation. When stalled the rotor would maintain a high coneing angle of about 10 degrees and spin at a fraction of its autorotative rpm. Often, the rotor would kick into pure autorotation as the tunnel speed was increased, requiring the tunnel operator to quickly drop the tunnel speed to avoid overspeeding the rotor. For this case, even when the tunnel speed was increased to 63 fps, the rotor would not enter full autorotation. When the rotor was retested with the blade pitch set to 1 degree, it quickly entered a full autorotation of 1658 rpm at the lowest possible tunnel speed (24 fps). Since the best forward flight performance was achieved for a blade pitch angle of 3 degrees, it was decided to increase the magnitude of feather/flap coupling to -1.0 which was estimated to allow the rotor to enter full autorotation with the desired forward flight pitch angle. Therefore; most of the data presented is for a $d\theta/d\beta$ of -1.0.

Given a feather/flap coupling ($d\theta/d\beta$) of -1.0, the next step was to determine the effect of blade pitch angle on performance. Figure 3 shows the lift to drag ratio (L/D) of the autogyro model (including parasite drag of the hub,mast, and body) as a function of angle of attack for different blade pitch angles. The body, mast, and hub were tested without the rotor and were determined to have an effective parasite drag area of 7.48 sq. in. For a blade pitch angle of 2.5 degrees at 18 degrees angle of attack the parasite drag was only 2.8% of the total drag while at 7 degrees

angle of attack parasite drag accounted for 20.6% of the total drag. Figure 4 shows the corresponding rotor advance ratios as a function of angle of attack. All data shown in these two figures was taken at a rotor rpm of about 1100 to keep the average blade chord Reynolds number constant (150,000). Figure 3 shows how sensitive rotor L/D is to the rotor blade pitch angle. The best L/D was achieved with a blade pitch angle of 3.4 degrees. Increasing theta (blade pitch angle) by .6 degrees to 4.0 degrees resulted in a dramatic drop in L/D. For a theta of 3.4 degrees, L/D's close to 4.0 were achieved. In fig. 4, it is evident that 3.4 and 2.5 degrees of pitch gave the lowest advance ratios or lowest airspeed required to reach 1100 rpm. Figure 5 gives the thrust coefficient, Ct, as function of angle of attack for the different pitch angles tested. Ct increases slightly with angle of attack, corresponding to a decreasing advance ratio.

Early into testing it became evident that rotor rpm had a large effect on rotor performance. For a fixed angle of attack, the rotor L/D and lift coefficient increased with rotor rpm. Figure 6 shows the effect of rotor rpm on L/D, and fig. 7 shows the effect on rotor lift coefficient. The results shown in fig. 7 are probably due to the increase in the average blade chord Reynolds number which is a linear function of rotor rpm. The average blade chord Reynolds number discussed is a thrust weighted average. In this Reynolds number range (150,000 to 219,000), airfoil aerodynamic performance improves significantly with increasing Reynolds number. The effect of low Reynolds numbers is accentuated by the fact that the retreating blade which has the lowest local Reynolds number (lower than the average for the rotor) is also operating at the highest lift coefficient due to the flapping motion of the blade. This retreating blade effect becomes more evident with increasing advance ratio. The rotor was structurally analyzed to be safe for operation up to 1700 rpm which determined the maximum Reynolds number which could be tested, but model vibration concerns limited the amount of testing done above 1100 rpm.

The rotor with a pitch angle of 2.5 degrees was tested at 90 degrees angle of attack to verify that the increased feather/flap coupling was sufficient to cause the rotor to self-start and enter full autorotation in a vertical descent. The tunnel was run at its lowest possible speed, about 24 fps, and the rotor quickly spun up to 1680 rpm. Unfortunately in the closed test section it was not possible to take meaningful vertical descent performance data due to wall effects. For example, the dynamic pressure without the rotor was 0.67 psf, and the rotor generated 11.8 lbs of drag with a disk area of 9.62 square feet (60% of the tunnel cross-section). Ignoring wall effects the calculated effective CD for the rotor was 1.83 while the expected value was 1.2.[2] Nevertheless, the test did verify the effectiveness of the feather/flap coupling with respect to autorotation self-starting.

The aerodynamic power required to fly is a very important consideration for the application of the autogyro as a decoy vehicle; especially if electric propulsion is to be used. Because of the relatively poor energy density of available batteries it is critical to keep the power requirements to a minimum, otherwise, the decoy will not have enough flight duration to be effective. Figure 8 shows the aerodynamic power (drag times velocity) normalized for a lift of 4.5 lbs as a function of angle of attack. For this model, with its fairly low chord Reynolds number, the decrease in airspeed required to generate 4.5 lbs of lift with increasing angle of attack more than offsets the decrease in L/D. Therefore; the optimum flight condition with respect to power required occurs at the very high angle of attack of 16 degrees. The optimum angle of attack for an actual full scale decoy vehicle would probably be closer to 10 degrees because the small decrease in power above 10 degrees would not justify the increase in propeller diameter and gear drive ratio required to attain the same propulsive efficiency at the lower airspeed.

CONCLUSION:

This experiment successfully demonstrated the use of

feather/flap coupling to allow a rotor with a positive pitch angle at a small coneing angle (2-3 degrees) to automatically enter autorotation at an angle of attack of 90 degrees. From this experiment, it was determined that a feather/flap coupling of -1.0 with a maximum coneing angle of 21 degrees is sufficient to allow the rotor to enter full autorotation starting from a vertical descent with rotors stopped. If for the decoy vehicle design, the rotors begin autorotation at the launch apogee, the high initial airspeed (around 150 fps) should accelerate the rotors to flight rpm (around 900) in a few seconds. The effect of the Delta-3 hinge on forward flight performance was to improve L/D slightly by reducing the rotor flap back angle. The improvement in L/D was offset somewhat by a decrease in rotor lift coefficient.

The rotor's performance in forward flight and the effect of the average blade chord Reynolds number were measured. For example, a change in average blade chord Reynolds number from 150,000 to 219,000, increased the L/D from 3.82 to 4.13 and increased rotor CL from 0.178 to 0.216. Planned autogyro decoys will probably operate with an average blade chord Reynolds number of over 300,000 which should result in superior performance compared to this model. Future autogyro models may be designed to allow operation at up to 2700 rpm which will bring the average blade chord Reynolds number up to this range. Additionally, airfoils optimized for operation at these low blade chord Reynolds numbers could be used in the rotor blade design to improve rotor performance.

References:

[1]Wheatley, J. B., and Bioletti, C., "Wind-Tunnel Tests Of 10-Foot-Diameter Autogiro Rotors", NACA Report No. 552, 1935.

[2]Gessow, A., and Myers G. C., *Aerodynamics of the Helicopter*, Frederick Ungar Publishing Co., NY, 1967.

NOMENCLATURE:

ρ	air density
α	rotor angle of attack
θ	blade pitch angle
β	rotor flap angle
V	airspeed
ω	rotor rotational speed (radian/second)
rpm	rotor revolutions per minute (clockwise)
R	rotor radius
c	rotor blade chord
L/D	lift to drag ratio
Vt	average rotor tip speed (ωR)
μ	advance ratio ($V\cos(\alpha)/Vt$)
Ct	thrust coefficient ($T/(\rho\pi R^2 Vt^2)$)
CL	rotor lift coefficient ($T\cos(\alpha)/(\frac{1}{2}\rho V^2)$)
$d\theta/d\beta$	change in theta with beta (Delta-3 hinge)

Re_c(ave) average chord Reynolds number

$Re_c(ave) = (0.8 \times Vt \times c \times \rho)/\text{viscosity}$

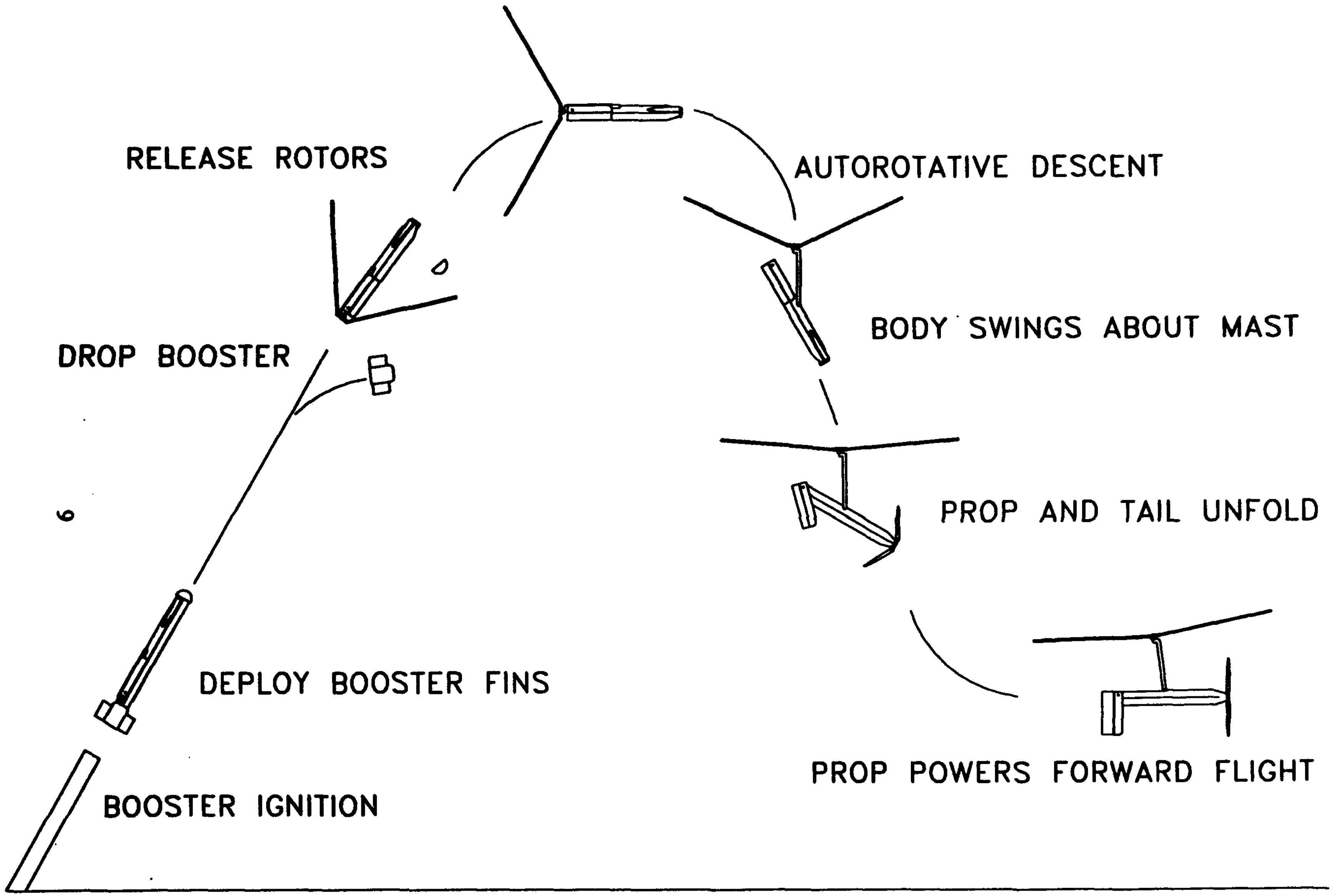

FIGURE 1: AUTOGYRO DECOY DEPLOYMENT

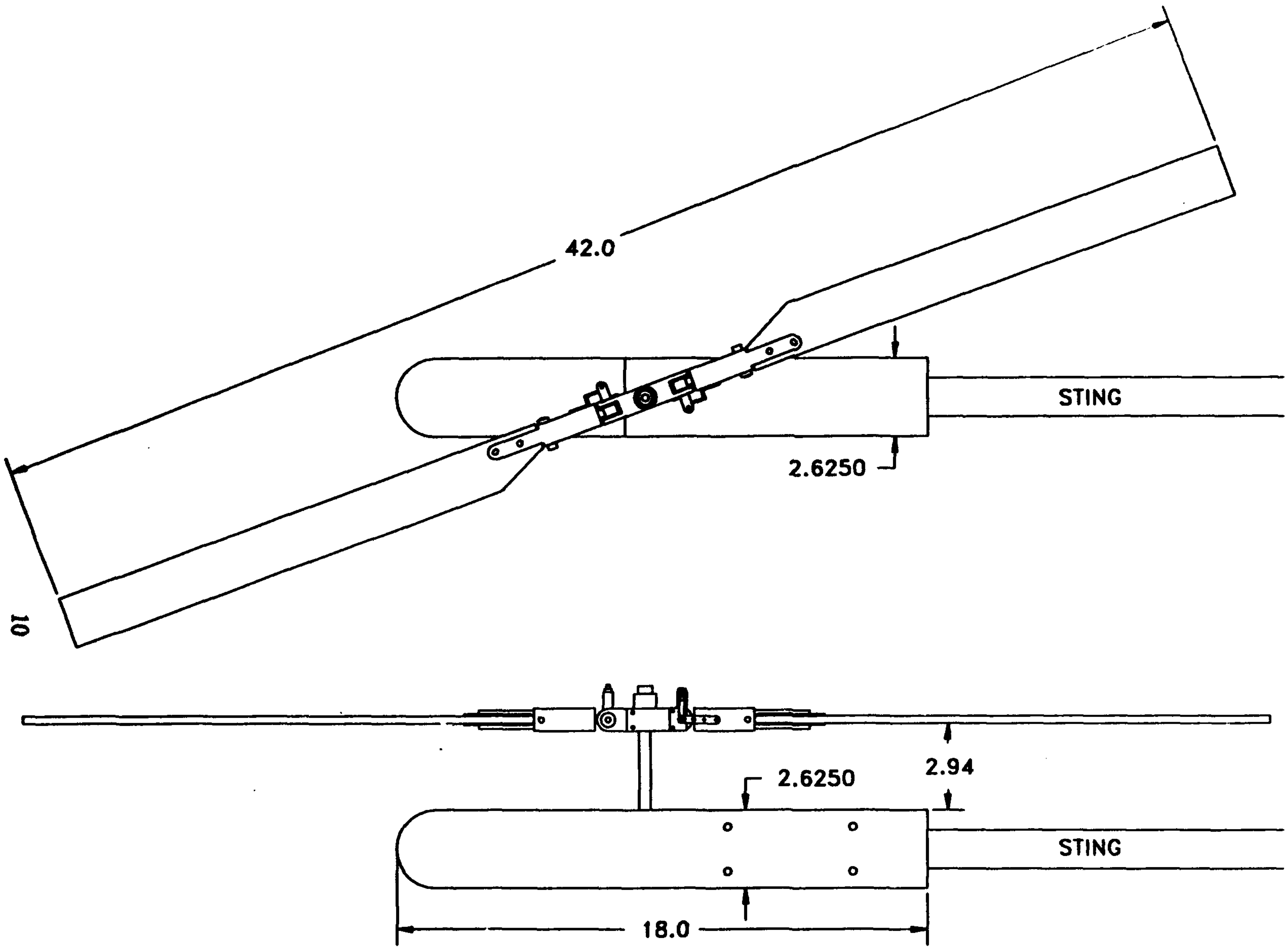

FIGURE 2: AUTOGYRO WIND TUNNEL MODEL

FIGURE 3: L/D VS. ALPHA.
RPM=1100, DTDB=-1.0

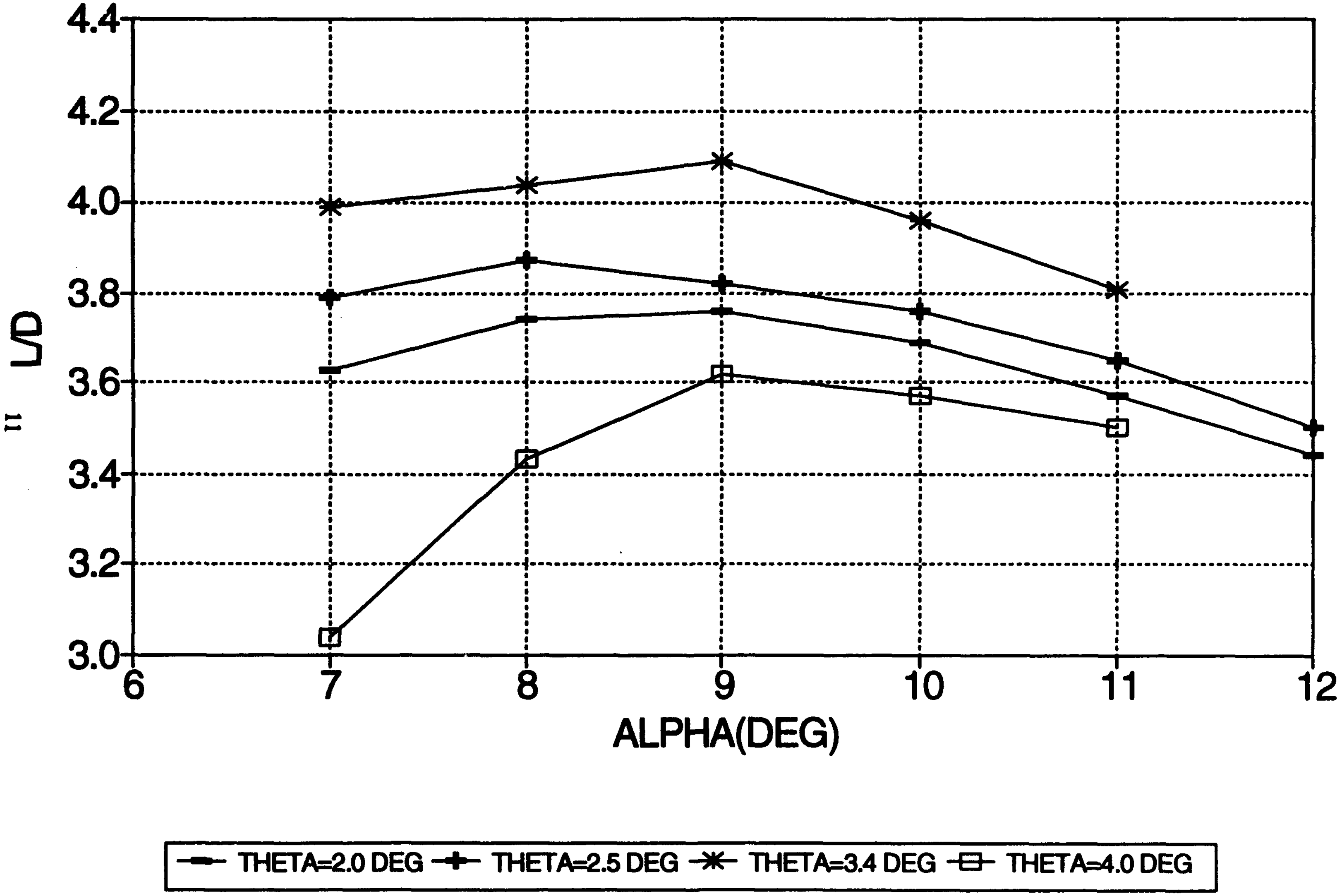

FIGURE 4: MU VS. ALPHA

RPM=1100, DTDB=-1.0

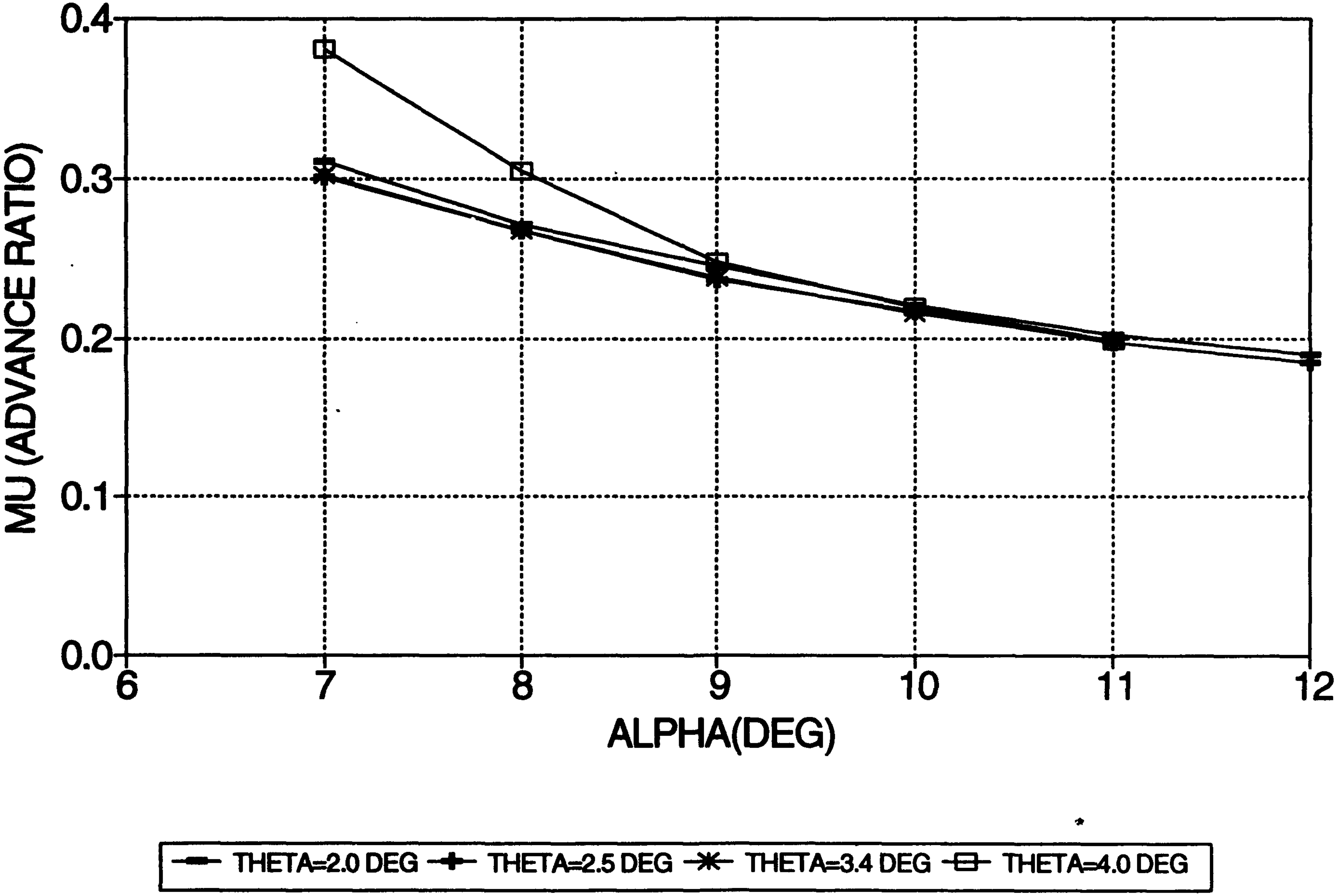

FIGURE 5: CT VS. ALPHA

RPM=1100, DTDB=-1.0

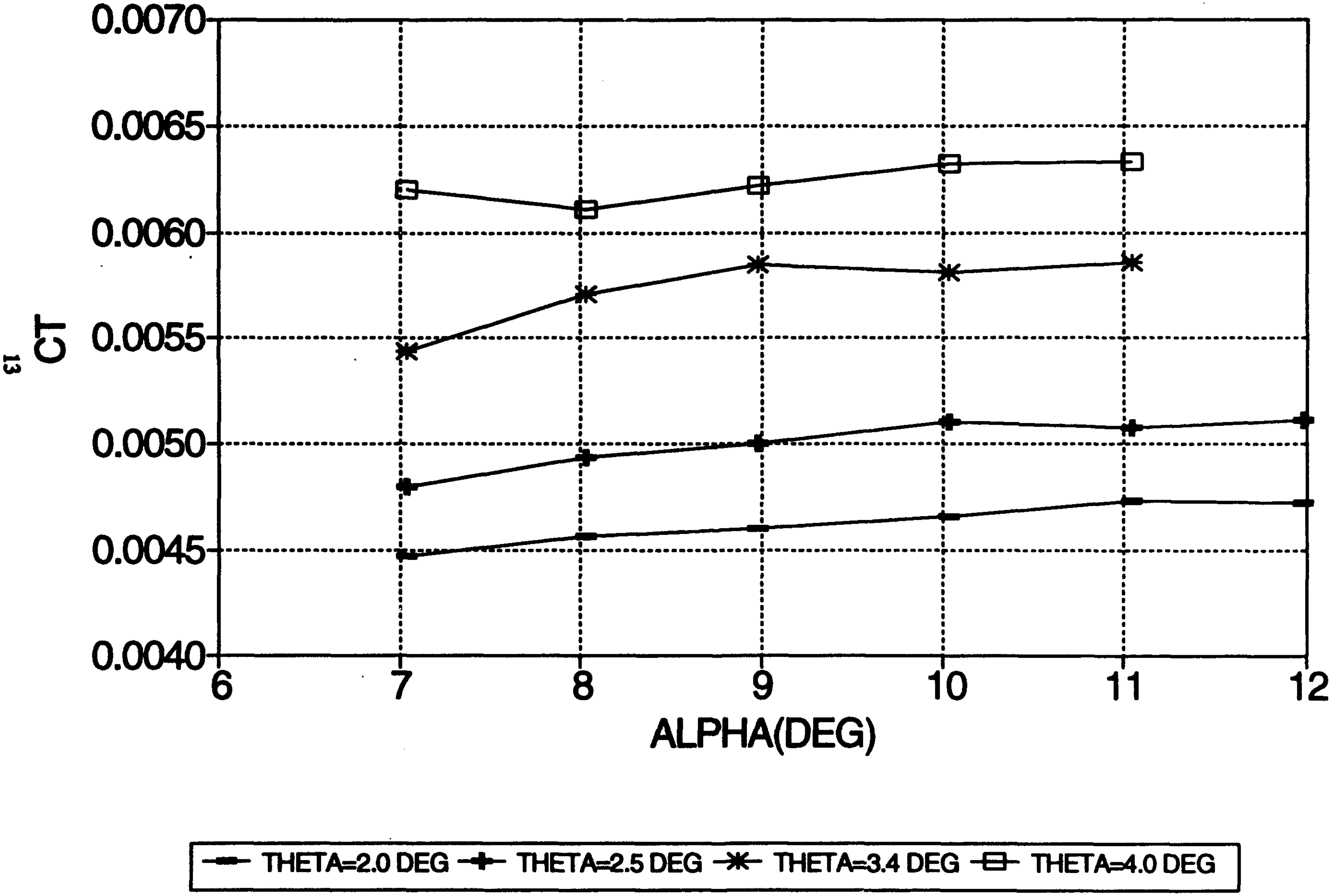

FIGURE 6: L/D VS. RPM
THETA=2.5 DEG, ALPHA=9 DEG

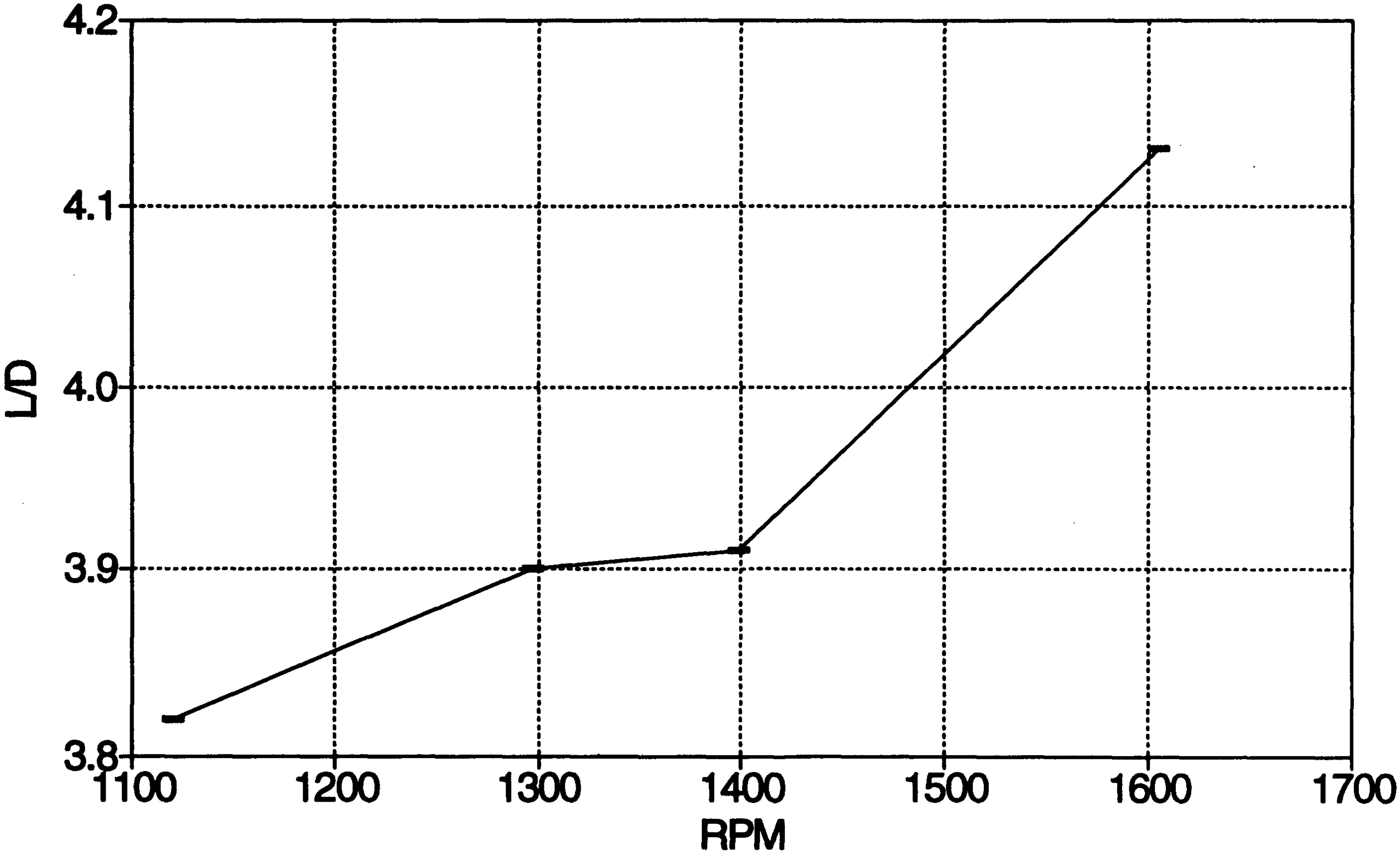

FIGURE 7: CL(ROTOR) VS. RPM
THETA=2.5 DEG, ALPHA=9 DEG

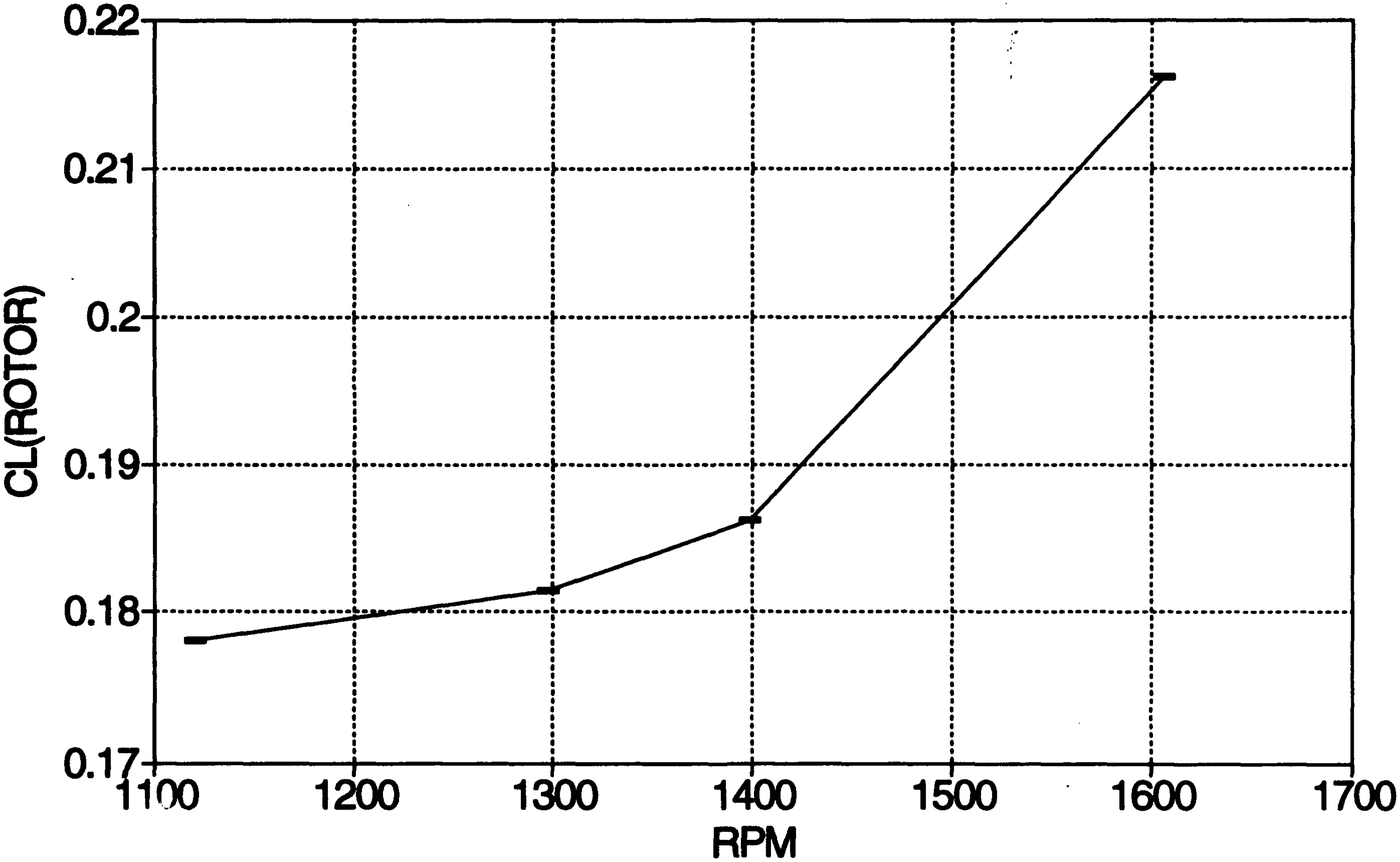

FIGURE 8: POWER REQUIRED VS. ALPHA
THETA=2.5 DEG,ALPHA=9 DEG,LIFT=4.5 LBS